



Full Length Article

Experimental understanding on the dynamics of micro-explosion and puffing in ternary emulsion droplets

Madan Mohan Avulapati^{a,b,*}, Thanos Megaritis^a, Jun Xia^a, Lionel Ganippa^a^a College of Engineering Design and Physical Sciences, Brunel University London, Uxbridge UB8 3PH, United Kingdom^b Indian Institute of Technology Tirupati, Tirupati, Andhra Pradesh 517506, India

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ABSTRACT

Dynamics of puffing and micro-explosion phenomena occurring in ternary fuel emulsion droplets under high temperature environment were explored using high speed backlight imaging technique. A single droplet composed of diesel-biodiesel-ethanol emulsion was placed at the tip of a 75 μm gauge thermocouple and introduced rapidly into a furnace maintained at 500 °C. Several interesting features such as oscillation of suspended droplets, physical transformations occurring within the droplet, vapour expulsion, puffing, micro-explosion, sheet formation, perforations, growth of perforations, sheet disintegration and rotation of secondary droplets were observed. High resolution image analysis revealed separation of emulsion components within the core of the suspended droplet, which appeared either as a single nucleus or multiple nuclei. Two distinct types of micro-explosion were identified. For droplets encountering a single nucleus at the core resulted in a stronger vapour expulsion followed by intense micro-explosion. For droplets having multiple nuclei at the core resulted in a weaker vapour expulsion and slower growth of droplet prior to micro-explosion. Both types of micro-explosion process resulted in a number of child droplets. For the case of strong vapour expulsion nearly 80% of its child droplets have their sizes distributed within 150 μm compared to 60% for weaker vapour expulsion. The child droplets that were generated from the primary events of both puffing and micro-explosion cascaded further into secondary and tertiary events of puffing and micro-explosion in freely suspended environment.

1. Introduction

Atomisation of liquid fuel produces a number of relatively smaller size droplets that leads to rapid evaporation, improved mixing and reduced soot formation in aircraft engines and in other power generation applications. Atomisation process can be enhanced when immiscible fuels of different boiling points are chemically bonded through a surfactant to form an emulsion. When emulsion droplets are exposed to higher temperature it undergoes preferential evaporation, triggering puffing and micro-explosion to form a number of smaller size droplets that enhances mixing [1]. Puffing is a process where a part of emulsion droplet expels a mixture of liquid/vapour jet that disintegrates into smaller droplets due to rapid evaporation of higher volatile components of emulsion. Flash evaporation of lighter components in an emulsion droplet leads to micro-explosion, where the whole droplet fragments instantaneously to form a large number of smaller size droplets. Studies have established that multicomponent fuel droplets with vastly different volatile components explode violently during combustion [2,3]. During vaporisation or combustion of a multicomponent fuel droplet,

higher volatile fractions tend to reach thermodynamically metastable superheat temperature, which leads to nucleation and bubble growth. Rapid expansion of vapour inside a droplet results in either total or partial disintegration of the liquid droplet.

Micro-explosion phenomenon has been observed in water–diesel emulsion fuels, which are widely used to control NO_x emissions in engines [4–6]. These studies have shown that the size and distribution of water droplets inside the emulsion droplet affects micro-explosion significantly. Khan et al [7] studied puffing and micro-explosion of water-in-diesel emulsion under Leidenfrost effect, and found that micro-explosion and puffing frequency was influenced by the droplet diameter. The size and velocity of secondary droplets from micro-explosion of water-in-diesel emulsion were measured by Tarlet et al. [8] to study energetic balance within micro-explosion using water in sunflower oil emulsion. Shinjo et al. [9] studied the effects of puffing on fuel/air mixing in a single droplet as well as in multiple droplets of decane/ethanol mixture under convective conditions using DNS. It has been shown that in a rapid compression machine, single droplet composed of water-in-n-decane undergoes puffing and micro-explosion

* Corresponding author at: Indian Institute of Technology Tirupati, Tirupati, Andhra Pradesh 517506, India.

E-mail addresses: madan.avulapati@brunel.ac.uk, madan.avulapati@iittp.ac.in (M.M. Avulapati).

under high pressure combustion conditions [10]. Melo-Espinosa et al. [11] have shown that by increasing in the concentration of surfactant in water-in-diesel emulsion inhibits puffing and micro-explosion behaviour. Moussa et al. [12] conducted detailed parametric study, which includes the effects of varying the size of dispersed water droplet in water-in-diesel as well as sunflower oil in diesel emulsions. It was concluded that along with water droplet size and heating temperatures, viscosity of the oil and purity of the water also influences the micro-explosion behaviour of water-in-oil emulsions.

Puffing and micro-explosion have received more attention in recent times due to the increased use of renewable alternative fuels. Biofuels that are derived from biodegradable materials can reduce toxic emissions and the overall life cycle emission of carbon dioxide, when burned as a fuel [13–18]. Blending of these renewable fuels or liquids of wider boiling point fractions in the presence of a surfactant creates emulsions, which undergo puffing and micro-explosion upon rapid heating [19]. The fatty acid constituents present in biodiesel serves as an emulsifier when mixed with diesel-ethanol blends. Renewable nature of both ethanol and biodiesel makes diesel-biodiesel-ethanol emulsion a promising alternative fuel. Zhang et al. [20] experimentally studied puffing of biodiesel-butanol droplets and showed that puffing occurs in these types of droplets in two modes. The first mode, termed as core mode, is a periodic process where bubble nucleation growth and rupture occurs inside the droplet. In the second mode, bubble nucleation occurs at the surface which results in many small child droplets. They have further studied the effect of n-butanol concentration in fatty acid methyl esters (FAME) on puffing characteristics over a wide range of concentrations between 0 and 75% of n-butanol [21]. Coughlin and Hoxie [22] conducted experiments on single droplet combustion characteristics of ternary mixture containing pentanol, butanol and soybean vegetable oil and found that equal volumetric blends of pentanol/butanol/soybean oil leads to violent explosion. Recently, Kim et al. [10] studied evaporation of emulsified fuel droplet at elevated pressure and temperature conditions and found evidence of puffing of emulsion droplets under these conditions. Studies by Zhang et al. [23] and Wang et al. [24] showed that micro-explosion phenomena in emulsion droplets can occur in sprays at high temperature and pressure conditions.

Most of the studies on droplet micro-explosion have been primarily focused on parametric analysis such as composition of the droplets, size of distributed phase, effect of gas temperature and effect of experimental methods. Very limited studies have been focused on droplets dynamics during micro explosion process. Hence, the present study explores the dynamics of vapour expulsions, puffing and micro-explosion processes in a ternary micro-emulsion droplet consisting of diesel-biodiesel-ethanol. The effect of thermo-physical transformations in the core of a ternary emulsion droplet and how this influences puffing and micro-explosion processes were elucidated using high resolution, high frame rate backlight imaging technique.

2. Experimental setup

In this work, a micro-pipette was used to place a ternary fuel emulsion of approximately 1.5 μl capacity on the junction of a thermocouple wires having a thickness of 75 μm . The emulsion droplet placed on the thermocouple corresponds to a diameter of approximately 1.4 mm. The thermocouple with the suspended droplet was traversed rapidly through a small opening into a high temperature furnace. Since the size of thermocouple is less than 1/10th of the droplet size, its contribution towards triggering micro-explosion or puffing remains relatively insignificant for the parent droplet suspended on a thermocouple. The schematic of the experimental setup used in this study is shown in Fig. 1. The furnace consists of a cylindrical clamp heater with optical access at both ends. A controller was built to set the furnace at a pre-defined temperature. Once the droplet enters into the furnace, a position sensor placed on the traversing rail triggered both the light and the high speed camera, which were placed at two ends of

the furnace for backlight imaging of the droplet. To observe various processes occurring external to the droplet, different set of images were acquired at a frame rate of 12,500 fps with the camera exposure time set to 0.3 μs . High magnification images of the droplets were also acquired at a frame rate of 2000 fps with an exposure of 2.5 μs to observe the transformation occurring inside the droplet. Fuel emulsions of various mixture proportions of diesel, biodiesel and ethanol were prepared using a magnetic stirrer at a temperature of 25 $^{\circ}\text{C}$. Emulsions were prepared on the basis of mass ratio by weighing individual components of the emulsions using a digital mass balance with a second decimal accuracy. Based on the previous works by authors [3], two ternary compositions of diesel-biodiesel-ethanol emulsions in the order of 20-30-50 and 20-40-40 were chosen for the present study to elucidate further the relation between the internal transformation to the external processes of puffing and micro-explosion. Hereafter no further reference will be made to the specific composition of emulsion as the observations are considered to be generic, particularly for higher alcohol concentrations of the ternary mixtures under consideration.

3. Results and discussion

When a ternary emulsion droplet consisting of diesel-biodiesel-ethanol was introduced rapidly into high temperature environment at 500 $^{\circ}\text{C}$, random and unpredictable chaotic events of either vapour expulsions or puffing or micro-explosion or a combination of these events were observed explicitly for these droplets. The emulsion constituents appeared to separate and the separated constituents were observed at the core of the droplet as either a single nucleus or as multiple nuclei. The implicit transformation from liquid to vapour of the emulsion constituent at the core of the droplet rapidly expands from within the droplets and exerts a pressure on the internal surface of the droplet. However convective currents causes oscillations to droplets, hence the nuclei and vapour bubble positions were not uniformly and concentrically distributed about the central core of the droplet; thus the internal pressures on the droplet surface are not uniformly distributed. Investigations have revealed that ternary emulsion droplets have two distinct characteristics of micro-explosion caused by strong and weak vapour expulsions.

3.1. Strong vapour expulsions

The first type of micro-explosion process was initiated by a small protrusion on the droplet surface as can be seen in Fig. 2 at 160 μs . This small projection could also be associated with the inception of a liquid jet emerging from the droplet surface due to high local internal pressure caused by bubble expansion and bursting closer to the surface; similar kind of small protrusion had also been observed for a very small puffing case as shown in Fig. 12(d). Rapid expansion of vapour bubble from inside the droplet expands and stretches the protruded liquid locally, which eventually pinches off from the droplet surface and punctures the surface of the liquid droplet. This creates a pathway for the vapour within the liquid droplet to expel at high pressure leading to strong vapour expulsion as shown in Fig. 2 at 240 μs . This strong vapour expulsion induced a force that disintegrates the liquid present in the path of expulsion and this resulted in a very fine mist of jet, which can be seen in Fig. 2 between the timeframes of 240 μs and 480 μs . Rapid expansion of vapour from within the centre of the droplet to the ambient lead to the formation of cup or half opened egg shell like structure having a void space in the centre and surrounded by liquid sheet. The liquid sheet stretched and expanded as time progress (480 μs –1280 μs), uneven thinning of the stretched liquid sheet lead to mild tearing at multiple locations causing perforations (1280 μs –3680 μs) on the sheet. These perforations grew due to surface tension effect and transformed the perforated liquid sheet into multiple ligaments, which appears to be in the form of distorted fullerenes structure (3680 μs –5280 μs). As time progresses (from 1244 μs) the ligaments breakup into droplets (6080 μs)

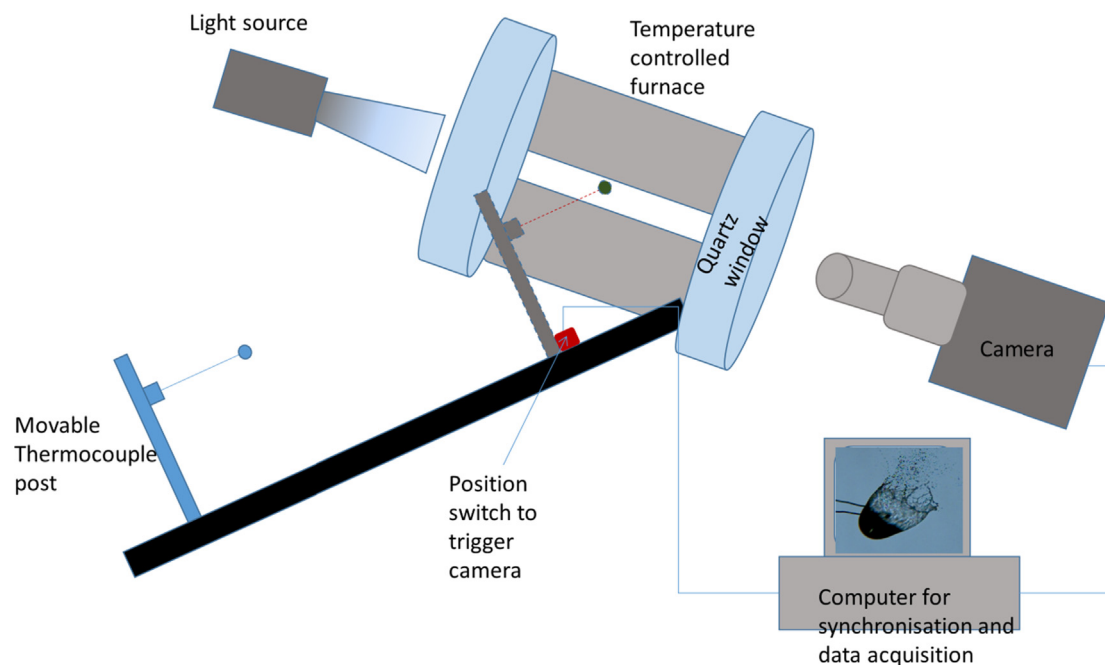


Fig. 1. The schematic of experimental set-up used to traverse a suspended droplet into a furnace with quartz windows on either side for backlit imaging of puffing and micro-explosion processes.

due to instabilities created by fluid and aerodynamic forces. From the acquired high speed images, the velocity of initial droplet cloud expulsion was calculated to be in the order 25 m/s. The high speed images revealed that child droplets and ligaments resulting from micro-explosion were observed to possess both translational as well as rotational motions. Rapid expulsion of vapour imparts bulk translational motion to child droplets, while the rotational motion was imparted due to tangential forces acting on the surface of child droplets when they were randomly positioned within the expulsion zones. The growth of perforation also imparted rotational motion. As the perforations grew,

liquid bridges (ligaments like structures) were formed between perforations. These liquid bridges tend to connect each other links to appear like a fullerene structure, where the links experienced twisting, stretching, bending and rotational movements. Eventually when these rims fragment they resulted in droplets having oscillating, translational as well as rotational motion. Rotational movements have been observed clearly in the high speed images for some of the ligaments shown in Fig. 3 (4480 μs – 9360 μs). Additionally, rotational motion of ligaments caused a relative motion between droplets and surrounding air that triggers Kelvin-Helmholtz and Rayleigh Taylor instabilities causing the

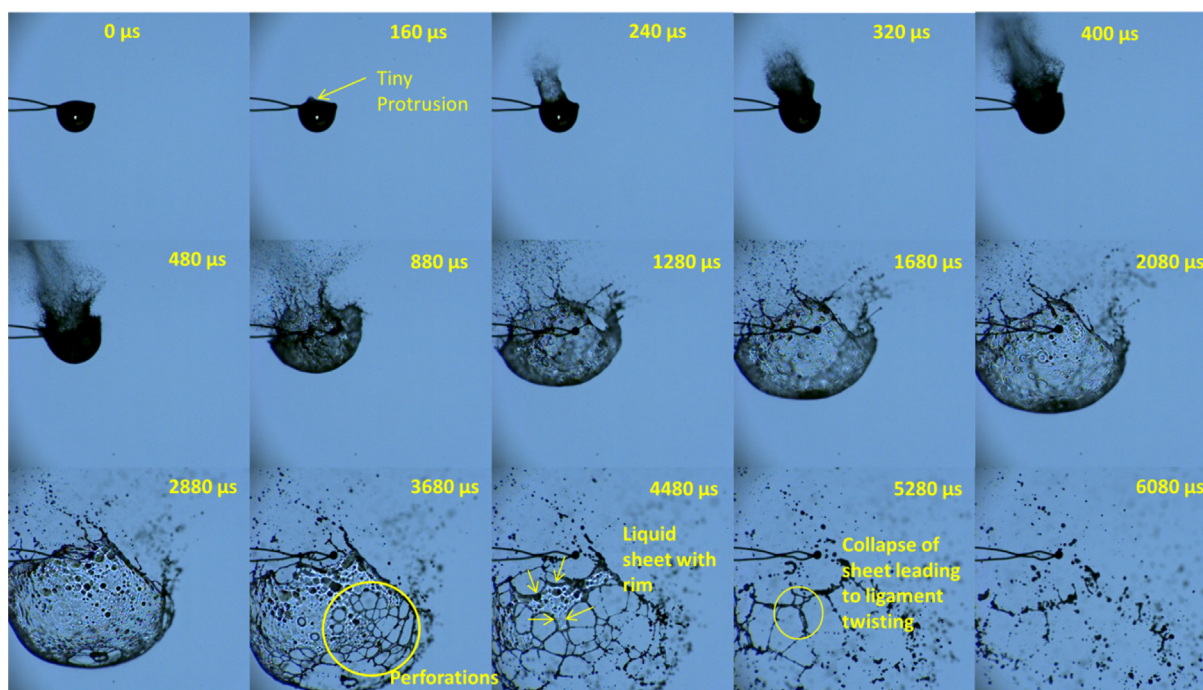


Fig. 2. Various phases of micro-explosion with strong vapour jet expulsion followed by sheet breakup. The time on each frame corresponds to the time after the start of micro-explosion process.

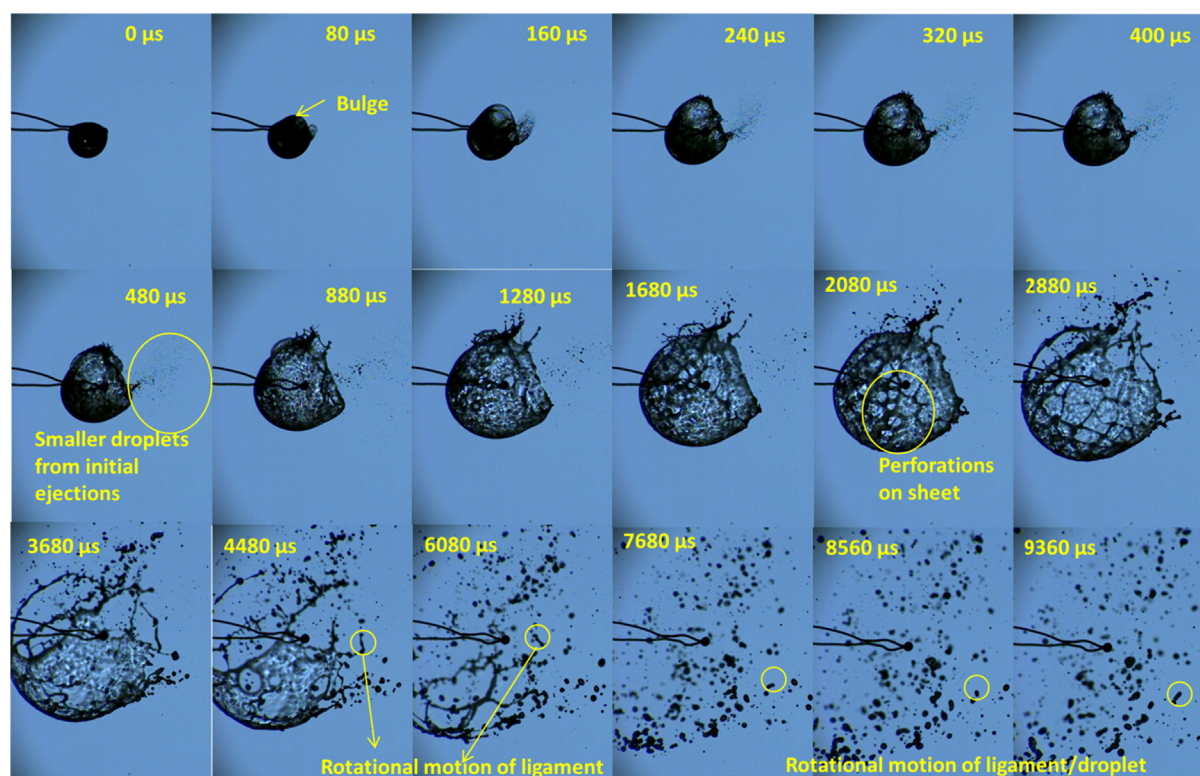


Fig. 3. Various phases of micro explosion with weak vapour jet expulsion. Hemi-spherical sheet formation, growth and disintegration can be observed in the image sequence.

ligaments to breakup into smaller droplets. The rotational speed of the droplets and ligaments were evaluated through image analysis and it was found to be in the order of 150–300 revolutions per second. The rotational speed of a droplet was determined by detecting the change in orientation of a particular droplet with time if the rotation is parallel to viewing plane and the change in area of a droplet with time if the rotation is perpendicular to viewing plane, which was converted to revolutions. The level of uncertainty with this rotation speed calculations will be less than 5%, as this analysis was performed by selecting those droplets that had oblate shape.

3.2. Weak vapour expulsions

In the second type of micro-explosion, unlike tiny protrusion of type 1 (strong vapour expulsion), a relatively dispersed bulge appears on the droplet surface as can be seen in Fig. 3 at 80 μ s. Expansion of vapour at the close vicinity of liquid exerts a pressure over a relatively larger area of the droplet and this appears as a bulge on the droplet surface. Contrary to type 1, only mild expulsion of vapour was observed and it pinches only a small part of liquid in the droplet to forms multiple droplets; and then thrusts the remaining droplet to be intact as can be seen at 160 μ s and 480 μ s. The vapour bubbles from within the liquid droplet expands and enlarges the bulge; the entire droplet size grew due to stretching of the liquid to form a film like hollow hemi-spherical ball of fullerene structure similar to that of type 1 but occurring at different time scale (880 μ s – 2880 μ s). From the images, it is clear that the intensity of vapour expulsions for type 2 micro-explosion is less intense when compared to type 1. However similar to first type, hollow liquid sphere expands with time and perforations start to appear and grow further to break the liquid into ligaments and droplets. It was observed that the size of child droplets resulting from the second type of micro-explosion process was relatively larger. The initial droplet cloud expulsion velocity was found to be in the order 8.5 m/s, which is 3 times lesser than first type of micro explosion. The sequence of events such as

initial droplet bulging, liquid expulsion, droplet growth, perforation and fragmentation for the second type of micro-explosion are shown in Fig. 3.

3.2.1. Growth rate, size distribution and velocity for type 1 and type 2 micro-explosion

The change in the size of droplet (ball like liquid film) during the processes of type 1 and type 2 micro-explosions were evaluated through image analysis at a particular location with respect to time. The acquired droplet size was normalised with initial droplet diameter to compare the growth rate of droplet/hemi-spherical liquid sheet. Comparison of the growth rate for two different types of micro-explosion processes are shown in Fig. 4. It can be seen that type 1 micro-explosion process facilitated a very fast growth rate of droplet/hemi-spherical liquid sheet where vapour expulsion velocities were also high. Higher growth rate also clearly indicates that stretching of liquid leads to thinner liquid sheet, which upon disintegration resulted in smaller droplets when compared to type 2 micro-explosions with weaker expulsions.

Sizes and velocities of secondary droplets resulting from both types of micro-explosion processes occurring in the anchored droplet were obtained through image processing. High speed images acquired after complete sheet break (at 7760 μ s for type 1 and 9360 μ s for type 2) were analysed to extract size and velocity. Calculating size and velocity at the same time instance will be difficult as the time scales are different. Moreover droplets tend to move out of the viewing area for strong micro-explosion and the depth of focus is very crucial for the analysis of droplet sizing and velocity. For the cases considered, micro-explosion of droplet was nearly symmetric about thermocouple axis and the depth of focus of the camera was adequate to capture droplets on one symmetric half of the sheet. Since the spatial resolution used in this work was 23 μ m per pixel, droplets making shadows below 5 pixels were not considered for size evaluation and its distribution. The uncertainty due to image post processing was estimated to be less than 12%. The

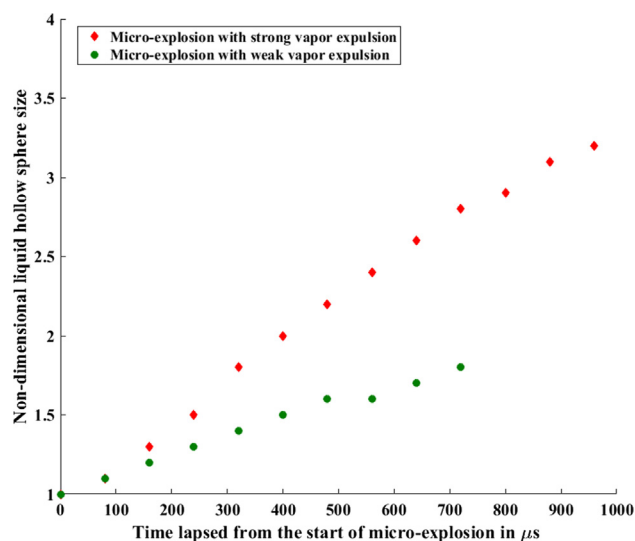


Fig. 4. Time resolved expansion of droplet consisting of hollow liquid sheet due to vapour expulsions for two different types of micro-explosion phenomenon. The droplet growth rate for type 1 micro-explosion was faster than type 2 micro-explosion.

probability distribution of secondary droplet sizes indicates that considerably larger number of droplets of size greater than 200 μm were present for the case of type 2 micro-explosion, which had weaker expulsion as shown in Fig. 5.

The scatter plot relating to droplet size and its velocity for both types of micro-explosion processes are shown in Fig. 6. Results indicate that micro-explosion with stronger vapour expulsion imparts higher velocities to droplets compared to micro-explosion with weaker expulsion. Also, the maximum velocities obtained by secondary droplets were almost twice for stronger expulsion case when compared to weaker expulsion. Hence, micro explosion with stronger expulsion enhances mixing and evaporation due to smaller drop size distribution combined with higher relative motion between droplets and the surrounding air.

3.3. Dynamics of puffing in primary droplet

Fig. 7 shows the dynamics of puffing process when a diesel-

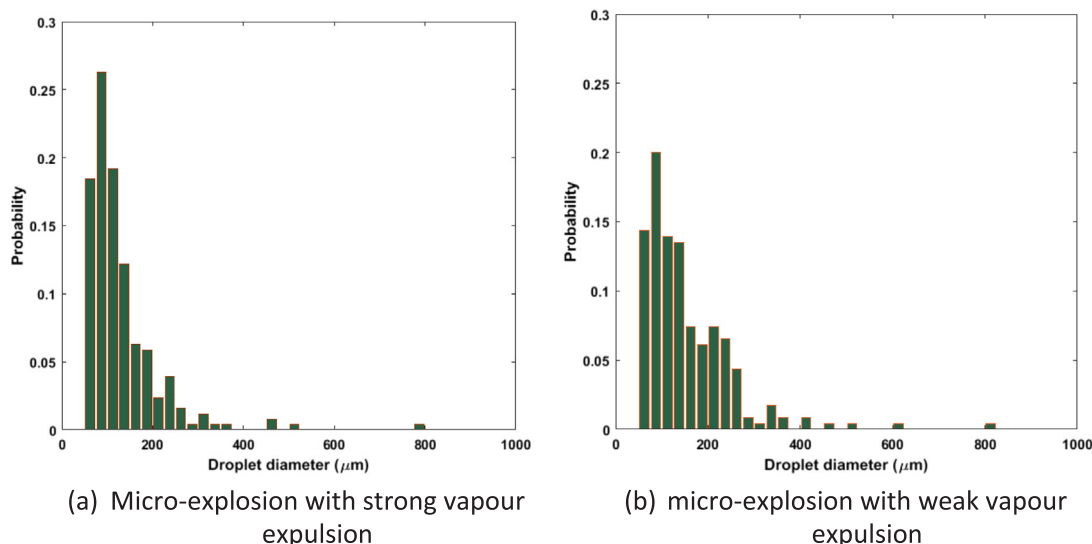


Fig. 5. The droplet size distribution for both types of microexplosion process show that weaker microexplosion have a greater number of droplets of sizes larger than 200 μm compared to strong microexplosion.

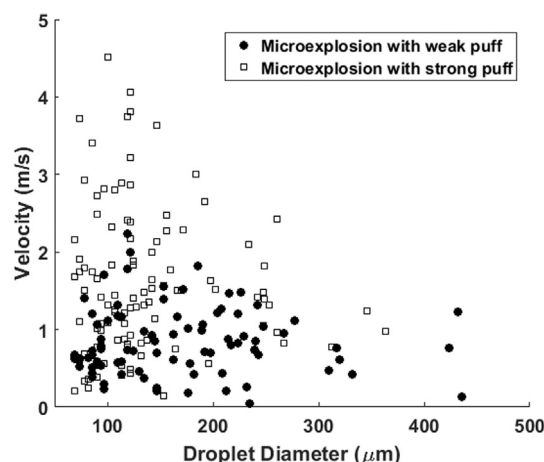


Fig. 6. Distribution of droplet size and velocity for both types of micro-explosion processes. Average droplet velocities are higher for explosion with stronger puff.

biodiesel-ethanol droplet was introduced into high temperature environment maintained at 500 $^{\circ}\text{C}$. Random and chaotic shooting of liquid jets from the parent droplet was observed, which further fragmented into smaller droplets. During puffing process the parent droplet did not completely disintegrate as only a very small proportion of fuel was dislodged in the form of jets but the major portion of the droplet was still anchored to the thermocouple. However, unlike type 1 and type 2 cases of micro-explosions, the core of the parent droplet was observed to be very unstable with bubbles of separated constituents of emulsions. Bubble formation and expansion closer to the droplet surface results in shooting of liquid jet from the droplet. The lengths of intact liquid jets were mostly observed to be in the order of twice the diameter of parent droplet. Relative motion between expelled liquid jets and surrounding air triggers Kelvin-Helmholtz and Rayleigh Taylor instabilities causing the jets to breakup into droplets. The calculated time scales for the breakup of these expelled ligaments into droplets were observed to be of the order of 200 μs .

3.4. Puffing and micro-explosion in secondary droplets

Puffing and micro-explosion was also observed in child droplets that were fragmented from the parent droplet either through puffing or

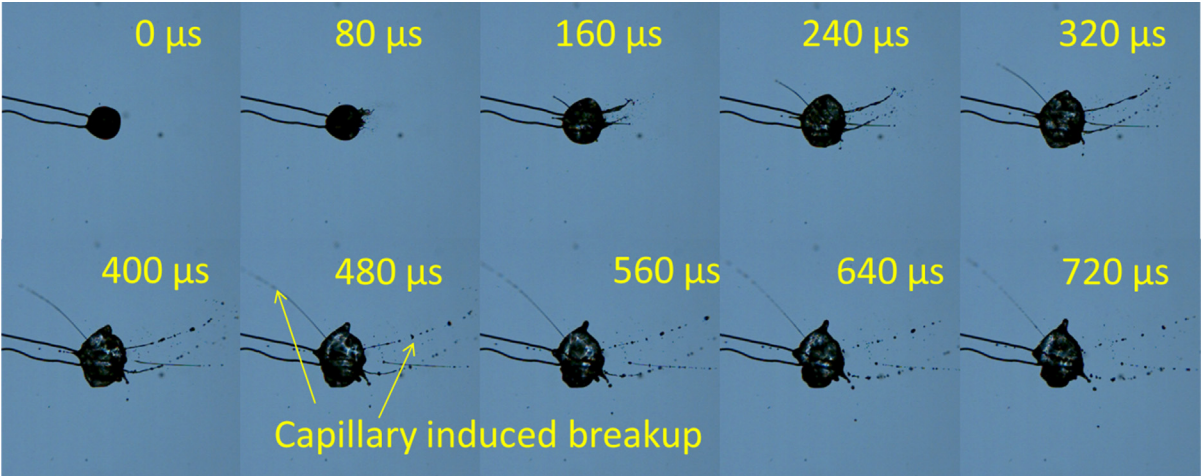


Fig. 7. Dynamics of puffing of Diesel-biodiesel ethanol droplet introduced into high temperature environment at 500 °C. Shooting of long liquid jets and very unstable droplet core was observed.

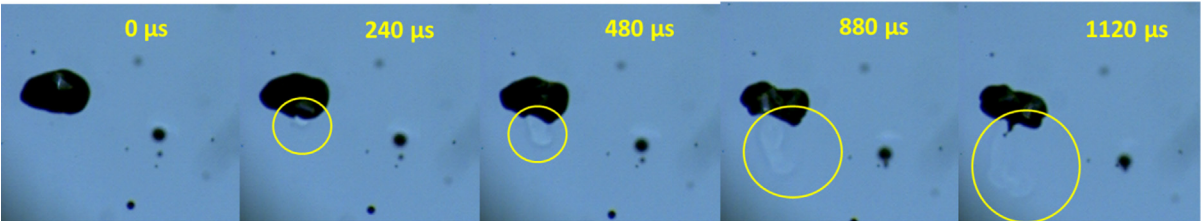


Fig. 8. Expulsion of vapours from the free secondary droplet resulted from explosion of parent droplet on thermocouple.

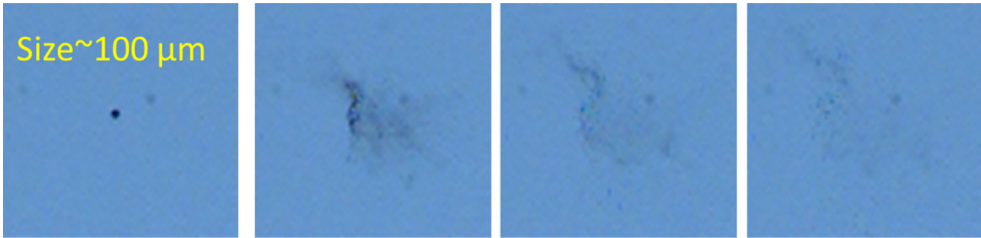


Fig. 9. Sequence of secondary droplet instantaneous explosion where complete process occurs within inter flame time of 80 μs.

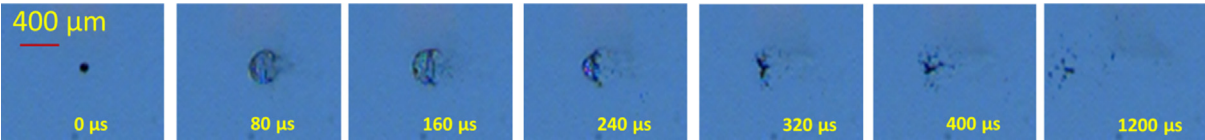


Fig. 10. Microexplosion of freely suspended secondary droplet, the processes are similar to droplets suspended on thermocouple.

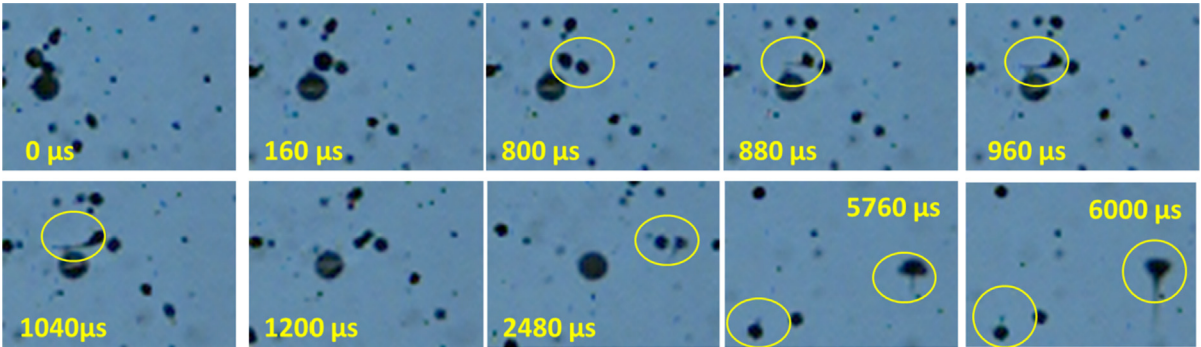


Fig. 11. Puffing process showing long stretches of liquid jets expelled from the child droplets, which are very similar to the process observed in parent droplet.

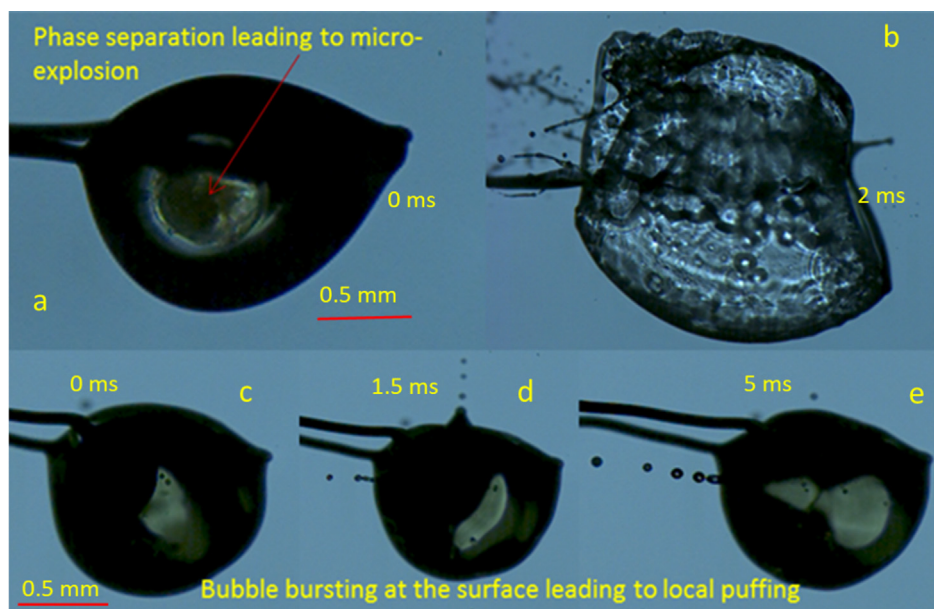


Fig. 12. Changes occurring inside the droplets before puffing and micro-explosion in anchored droplets. Separation of liquid components from emulsion is visible inside the droplet before micro-explosion and bubble nucleation in case of puffing.

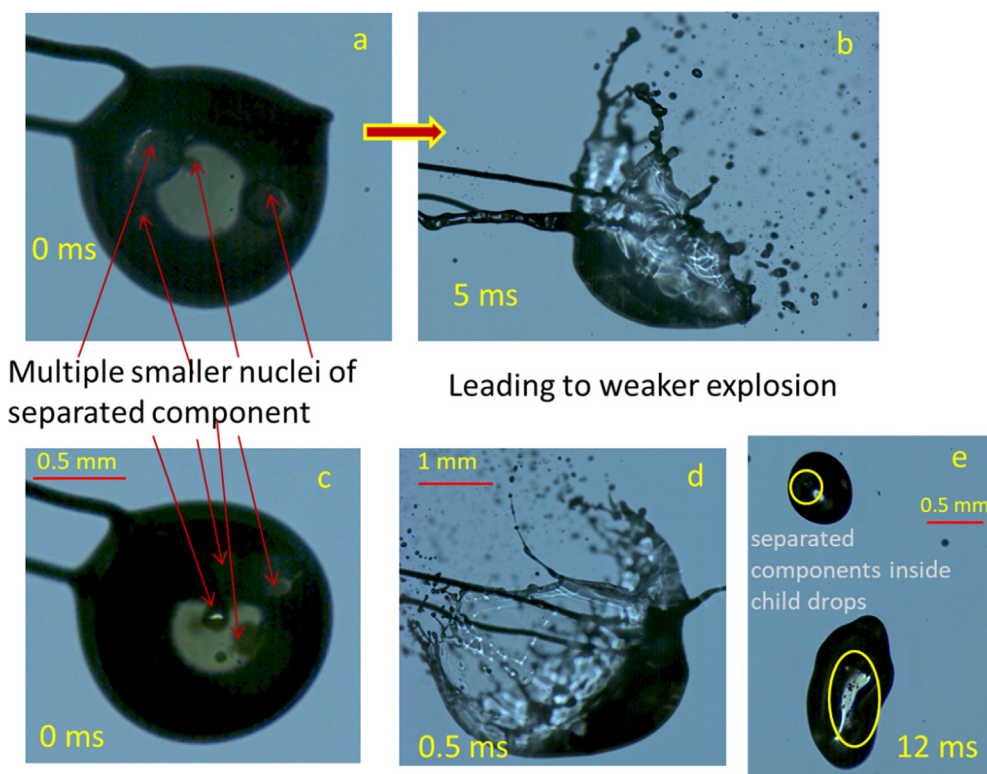


Fig. 13. Changes occurring inside the droplets before weaker micro explosion in anchored droplet. Separation of liquid components into multiple nuclei is clearly visible inside the droplet. Separated liquid component of emulsion was also observed in child droplets, which leads to puffing and micro-explosion in child droplets.

through type 1 or type 2 micro-explosion process. These droplets were freely suspended in air when compared to parent droplet which was anchored on a thermocouple. The processes occurring in both parent droplet as well as child droplets were similar. As similar characteristic features of puffing and micro-explosion events were observed for freely suspended child droplets and similar observations have also been reported by Mura et al. [25] for their water-diesel emulsion investigations. Various breakup processes occurring in secondary droplets are shown in Figs. 8–11. Vapour expulsion from the secondary droplet is

shown in Fig. 8, vapour was observed to leave the droplet with a velocity of the order of 2 m/s. Due to such low velocities of vapour expulsion, momentum was not strong enough to push the droplet significantly to form a sheet but it alters the shape of a droplet to some extent. This could be due to low amount of volatile component (ethanol) available in the secondary droplet. At the end of vapour expulsion process, small quantity of liquid from the secondary droplet was observed to emerge as a micro jet as shown in Fig. 8 at 1120 μ s.

A few of the secondary droplets exploded instantaneous into very

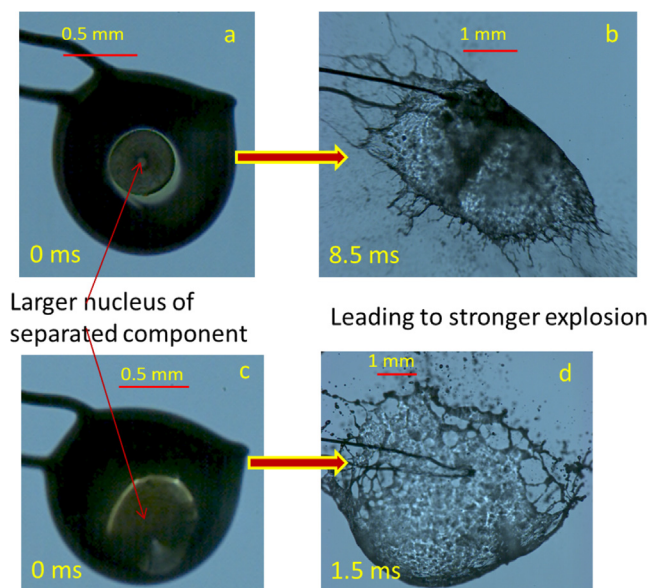


Fig. 14. Changes occurring inside the droplets before strong micro-explosion in anchored droplet. Volatile component of the emulsion separated to form a large nucleus and resulted in stronger micro-explosion.

fine droplets as shown in Fig. 9. The micro-explosion of the secondary droplet was extremely fast compared to primary droplet, the entire fragmentation of the secondary droplet was observed to occur within the inter frame time of 80 μ s. This type of fast explosion was observed in relatively smaller size droplets of about 100 μ m. Since the pixel resolution of the high speed data were at 23 μ m per pixel, the uncertainty in the time scale of micro-explosion for the above mentioned droplet size is high. Fig. 10 shows different stages of micro explosion processes occurring in secondary droplet of the size around 150 μ m. Similar to the anchored parent droplet, sheet formation, expansion and sheet breakup stages were also observed in the child droplet explosion.

Similar to that of parent droplet, puffing process resulted in thin long liquid jets expelled out from multiple child droplets as shown in Fig. 11. Even for child droplets, only small portion of liquid was expelled as micro jet, which resulted in even smaller size droplets. These observations revealed that the dynamics of both puffing and micro-

explosion scales across wide size ranges of droplets.

3.5. Linking internal droplet transformation to micro-explosion

To gain insights into physics behind puffing, vapour expulsions and micro-explosion process in a ternary emulsion of diesel-biodiesel-ethanol droplets, high resolution images were taken at a reduced frame rate of 2000 frames/sec at a pixel resolution of 7.5 μ m/pixel. The physical changes occurring within the parent droplets just before micro-explosion and puffing are shown in Figs. 12(a, c, d, e), 13(a, c) and 14(a, c). These images reveal separation of emulsion constituents inside the droplet before either micro-explosion or puffing.

The separated low boiling point ethanol component of emulsion occupied almost the internal region, which eventually undergoes phase change to form a single vapour bubble or several vapour bubbles. Bursting of these vapour bubble closer to droplet surface leads to puffing of the droplet as shown in Fig. 12(d, e). Formation of multiple nuclei from separated component (ethanol) in the core region of droplet leads to weaker micro-explosion. There could be several possible reasons for weaker micro-explosion; firstly the volatile component distributed over multiple locations within the droplet may not evaporate simultaneously. The strength of micro-explosion depends on the amount of volatile component evaporated; flashing of smaller amount of volatile component eventually results in weaker explosion. Also, the nuclei closer to the surface will evaporate faster relative to other nuclei, this inhibits heat transfer from surrounding air to all nuclei uniformly within the droplet and this also delays their evaporation. The presence of nuclei cluster within the droplet will also offer resistance to expanding fronts of vapour from multiple nuclei, and this effect of shielding is not present in a droplet having single bubble. Hence it can undergo rapid free expansion leading to larger droplet growth rate and stronger micro-explosion. The weaker micro-explosion due to shielding effect also resulted in relatively larger size child droplets with relatively lower velocities as discussed in Figs. 5 and 6.

Fig. 13 shows weak micro-explosion process, where relatively more quantity of liquid was left after micro-explosion compared to the case of strong micro-explosion, as shown in Fig. 14. The presence of volatile component in child droplet as shown in Fig. 13(e) confirms that all of the volatile component nuclei were not uniformly evaporated during primary explosion, which could be due to shielding effect. Evaporation of the volatile component in child droplet further triggers puffing and micro-explosion as shown in Figs. 8–11 and this enhances atomization.

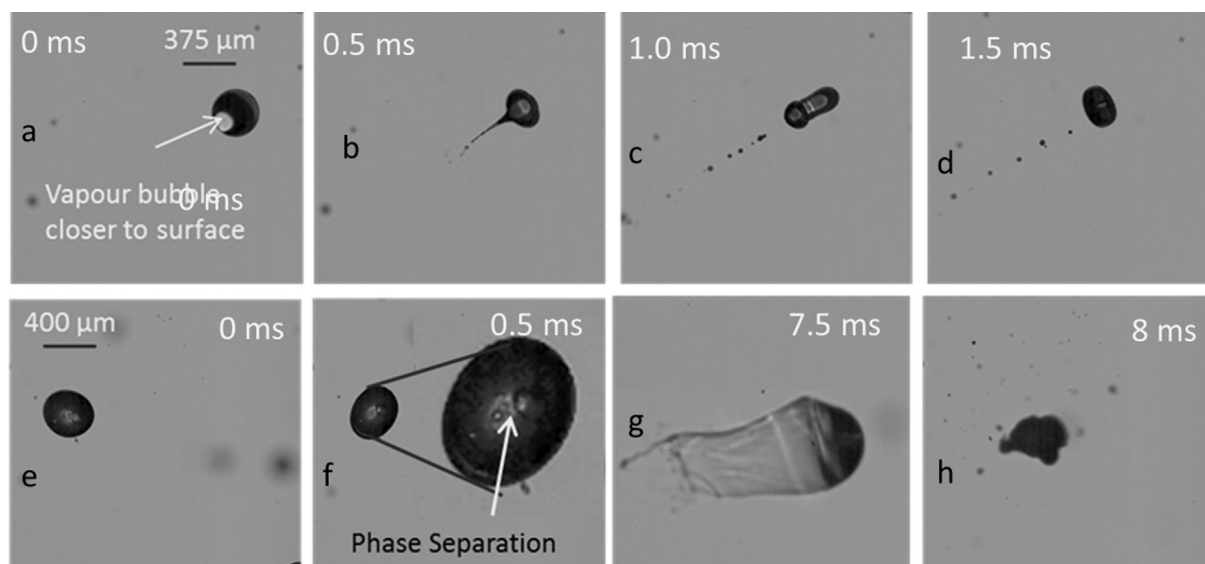


Fig. 15. Puffing and explosion process occurring in child droplets. Vapour bubble bursting closer to surface leading to puffing and component separation of emulsion leading to explosion with sheet formation.

Instead of multiple nuclei, if the volatile component of emulsion separates into relatively larger size nucleus (with very negligible number of vapour bubbles shielding the larger size bubble), this favours rapid vaporisation of nucleus and faster expansion of the droplet as seen in Fig. 4 and this leads to strong explosion causing complete disintegration of droplet as shown in Fig. 14.

Similar phenomena of component separation and formation of either single or multiple nuclei were also observed in child droplets as can be seen in Figs. 13(e) and 15. For the case of child droplets, the presence of ethanol constituent is of varying quantity and this was mainly dependant on primary puffing and micro-explosion process. Despite varying quantity of ethanol in child droplets, it still caused puffing and micro-explosion of varying intensity depending on the amount of ethanol present in the child droplet and this can be seen in Fig. 15. Internal changes occurring in freely suspended child droplets before puffing and micro-explosion were observed to be very similar to the anchored parent droplets. Vapour bubble formation and expansion closer to the surface resulted in puffing as shown in Fig. 15(a–d) which is very similar to the process shown in Fig. 12(c, d, e). Also, the presence of multiple nuclei inside the droplet resulted in weaker explosion as shown in Fig. 15(e–h) and this is very similar to the process discussed in Fig. 13(c, d). The phenomena of puffing and micro-explosion continued as long as ethanol constituent was present in cascaded droplets.

Acquiring puffing and micro-explosion process in a child droplet is extremely difficult as they are randomly displaced after complex fragmentation from the parent droplet. In this investigation, the camera was deliberately kept out of focus of the parent to capture secondary droplets that came in the focus plane of the high resolution investigation.

It was also observed that puffing process creates oscillation to the parent droplets, under strong oscillating conditions; instabilities caused capillary induced cleavage to break the part of parent droplet in some cases. The observed cascading effect of puffing and micro-explosions occurring in primary, secondary and tertiary size droplets in our experiments indicate that micro-explosion is scalable and it has the potential to reduce PM and to reduce the time scale of combustion to curtail NO_x emissions, which could be vital for emission control in larger size compression ignition engine.

4. Conclusions

Dynamics of puffing and micro-explosion occurring in ternary blends of diesel-biodiesel-ethanol introduced into high temperature environment at 500 °C were studied using high speed backlight imaging. The findings of the present study can be summarised as follows

- Two different kinds of micro-explosion processes were observed for ternary emulsion. Signature of the first type of micro-explosion process was strong vapour cloud expulsion and subsequent sheet formation and disintegration. In the second type of micro-explosion, initial puffing was weak and hence sheet growth was slower and resultant droplet size growth was relatively less when compared to first type. Due to faster growth rate of liquid sheet, breakup times were smaller for first type of micro-explosion when compared to second type.
- The child droplets and ligaments resulting from micro-explosion possess both translational as well as rotational motions, which increase relative velocity between droplet and surrounding air. Smaller droplet size distribution combined with higher relative motion between droplets and surrounding air will enhance mixing and evaporation.
- The dynamics of puffing and micro-explosion processes observed for freely suspended child droplets are similar to the dynamics of anchored parent droplet though the freely suspended child droplets sizes were more than two orders of magnitude smaller than parent droplet.
- Separation of emulsion constituents were observed within the

droplet prior to micro-explosion and puffing. Single nucleus of separated component within a droplet results into stronger explosion when compared to multiple nuclei resulting in weaker vapour expulsions and explosions.

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